Developments in wire bonding technology have been aimed towards the obvious requirements for increased speed and finer pitch as well as two other problem areas:

- how can the bond process be controlled to ensure optimised bonds of constant quality?
- how can the bond quality be monitored and documented, reliably and non-destructively?

This article provides a short description of the physical processes which occur during wire bonding and then goes on to describe the Bond Process Control Unit (BPC) developed by F&K Delvotec. The BPC is the only commercially available unit for on-line control of the bond process and is being used successfully around the world, in particular for aluminum wedge bonding. The BPC features have been expanded recently to include statistical processing capability making it an invaluable tool for efficient monitoring and control of the manufacturing process. The first section explains why bond process control is required and how it operates, the second section describes the statistical evaluation of the bond data which are collected for every bond.

Bond Process Control

F&K Delvotec has carried out many analyses of the physics of bonding over the years. A review of the results will be useful for understanding the operation of the bond process control unit.

Ultrasonic bonding of aluminium wire is a friction weld process, whereby two metals are pressed together at room temperature and are rubbed together ultrasonically at the same time. Essentially there are two steps to the process, the second step being subdivided into three phases:

1. Touchdown and pre-deformation

The bond wire is brought down flat onto the bond surface by the bonding wedge. Depending on the programmed parameters and the dynamics of the bonder, the mere act of bringing the wire into contact with the bond surface will cause the wire to be squashed or pre-deformed to some extent. This pre-deformation plays an important part in determining the quality of the subsequent welding process. The lattice structure of the bond wire and/or the bond surface will be changed significantly if the pre-deformation is too high and the quality of the subsequent bonds will suffer accordingly.

2. Ultrasonic Stage and Welding

By applying an ultrasonic frequency to the transducer, the wedge, which is connected to the transducer, vibrates along the wire. The amplitude of the vibrations, 1 to 5 microns, is very small compared to the 25 to 50 micron diameter of the fine wires typically used; on standard machines a frequency of 60 to 100 kHz is used. Initially the wedge and the wire move together creating friction at a constant pressure on the interface between the wire and the bonding surface. After a short time, the wire begins to deform and heat up and welding occurs. Both effects are crucial for the quality of the weld. Precise dynamic analysis of the bond surface temperature and wire deformation shows that the procedure can be split into three phases:

- **Cleaning phase:** In the short first phase usually lasting 4 to 10 ms hardly any deformation occurs and the temperature of the bond surface rises only slowly. The ultrasonic energy being applied is used mainly for surface cleaning - the removal of surface oxides and contamination layers - and heating, with only relatively small amounts being used for deformation. Throughout this phase, the wedge rubs the wire across the bond surface.
- **Mixing phase:** In the second phase, the temperature rises sharply and the wire deforms accordingly. The ultrasonic power is used now to level out the metal surfaces and to cause a distinct rise in the bond surface temperature. The metals are brought together until they are only one atomic lattice dis-

tance apart over as much as the interface area as possible; the elevated temperature enhances the diffusion of atomic lattice dislocations and relaxes the weld area. A partial weld ensues and the wire sticks to the bond pad. The wedge now rubs onto the essentially immobile wire thereby generating a further increase in temperature.

- **Diffusion phase:** No significant deformation or increase in temperature occurs in the third stage. The heat generated by the friction of the bond wedge on the surface of the wire causes the temperature of the bond area to rise thereby increasing the relaxation of the weld area. This tempering process stabilises the bond by „curing" the diffusion rich interface area and preventing it from becoming brittle.

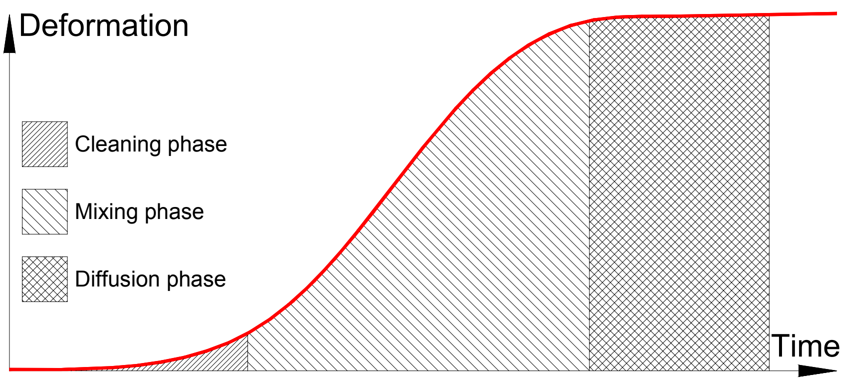

Figure 1:
Three phases of the deformation development

Every bond goes through the three phases described above although the length of each phase can vary for a number of reasons: the wire composition is not homogenous, the surface properties and contamination level vary. In an ideal situation, as soon as the deformation curve levels off, the energy supplied is reduced and is removed altogether shortly afterwards. However on most machines a very high maximum energy level is programmed to ensure that all bonds are made. This method accepts the risk of a large number of bonds receiving too much energy and thus being 'overbonded', resulting in a significant quality loss.

This is shown clearly in figure 2 which is a display of two typical deformation curves

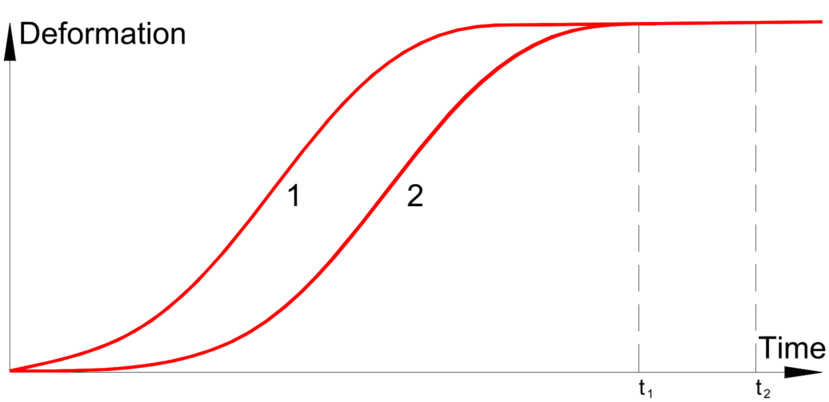

figure 2:
Deformation curves seen on a bonder without deformation control

as they would occur on a machine without bond process control. By the time t_1 has elapsed, the bond in curve 1 has already reached full deformation, whereas the longer, slower deformation of bond 2 requires a longer bond time t_2. To ensure that both bonds are sufficiently formed the ultrasonic power must be applied for all of t_2, but then too much power is applied to bond 1 resulting in a lower quality bond because of the overbonding.

On a conventional bonder the same ultrasonic energy is applied for all three phases described above, but in reality each phase requires a different level of energy to be applied. The first phase or surface cleaning phase requires more power than the second or mixing phase. The third phase is a diffusion phase and only requires power to heat the bond surface.

Bonding at a constant power and time is common practice but is not the best method. If it were possible to monitor the three bond process stages automatically during bonding and to regulate the US-Power accordingly, the bond quality could be improved significantly.

This capability, called Bond Process Control unit (BPC) was developed by F & K Delvotec and has been used for several years in most of the aluminum fine wire bonders delivered.

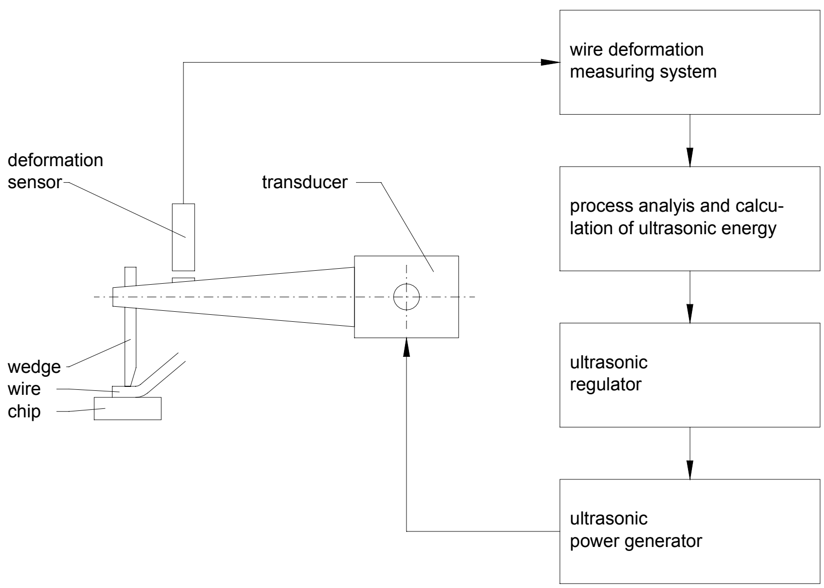

figure 3:
Bond process control for aluminium wire bonders

The prerequisites in the bonder are simple in concept and easily recognisable in *figure 3*. The key component is a high-resolution proximity sensor mounted on the transducer bearing, which measures the downward movement of the wedge after a successful touchdown and thus registers the ensuing deformation very accurately. The sensor signal is digitised by an A/D converter then processed by the controller which then regulates the US-power being applied depending on pre-defined reference values. At the same time the measured data and the bond curves can be displayed on a standard PC and stored away for processing.

Typical bond curves are shown in *figure 4*. The source bond, usually the bond on the board or substrate, is shown on the left-hand side of the monitor; the destination bond, usually the one on the semiconductor, is shown on the right hand side.

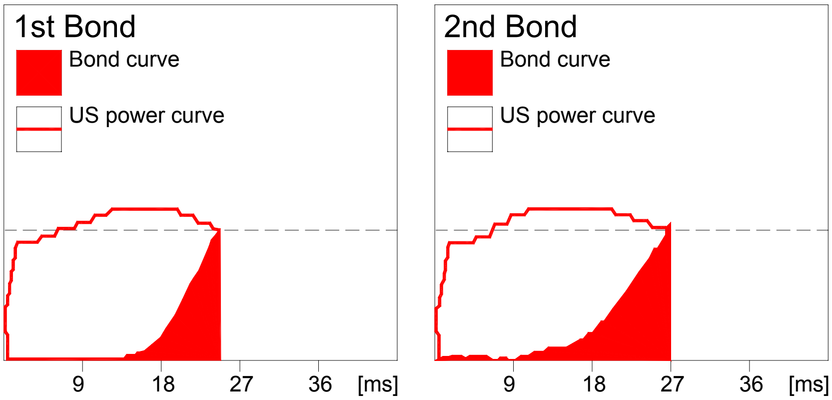

figure 4:
Deformation curves and bond parameters shown on the screen

Bond data: source		Bond data: destination	
US start power:	85	US start power:	85
Reference slope	65°	Reference slope	65°
Touch down steps	8	Touch down steps	8
Bond weight	20	Bond weight	20
Bond angle	0	Bond angle	0
actual deformation	103	actual deformation	105
min. deformation limit	35	min. deformation limit	35
max. deformation limit	250	max. deformation limit	250
Status (R,Q)	0,0	Status (R,Q)	0,0
prog. deformation	95	prog. deformation	95
Energy [Wms]	10	Energy [Wms]	10
Wire no.	12	Wire no.	12
Module no.	1	Module no.	1
Chip no.	0	Chip no.	0
Bond time	26	Bond time	28
Settling time	0	Settling time	0
max. bond time	45	max. bond time	45

One of the central issues in wire-bonding technology is the difficulty in monitoring and influencing the bond quality during the bond process and theories and attempts to solve this problem are as old as the technology itself. Control is usually restricted to optical inspection and destructive pull and shear tests on a sampling basis. In the day and age of zero defect manufacturing, this „blindfolded“ type of production is obviously unsatisfactory.

SPC supported evaluation of bond data

The BPC units in use generate a considerably higher yield of good bonds than that achieved on constant output machines. The bond development can be followed on the monitor, but, unless the bonder has been programmed to stop and request operator intervention in the event of a failure, the only way to check for bad bonds is to actually look for them on the monitor. However, it is not always necessary or desirable to interrupt the bonding sequence as the operator cannot repair the faulty bond immediately and can only mark it for checking or repair at a later date. For such applications the „bond process monitoring“ mode is now available. In this mode the stored bond data is not just displayed, it can be transferred to a database for simultaneous on-line or off-line processing. For each bond the BPC collects data on the minimum and maximum US-power, t he expired time, the predefined deformation and well as the deformation growth and the corresponding US-power applied. In addition user selected deformation parameters are established and are used for characterisation of each bond. This is usually the time for 20%, 50% and 80% of the final deformation to be reached, i.e. t_{20}, t_{50} and t_{80}. Furthermore, every bond entry within the database is assigned a freely selectable identifier, e.g. the magazine or lot number, as well as the date and the real time, updated in two second intervals, as can be seen clearly in figure 5. This enables a single bond to be identified specifically, even when millions of different bonds from different bonders and numerous substrate lots are stored in the same database. The database chosen is a modern SQL version which the user can process with any suitable programme such as Microsoft Excel or Access or Oracle etc. The user implements his own existing data processing packages; F&K Delvotec only supplies the data base, which can be expanded indefinitely and is limited only by the user's storage capacity. Normally the database is processed via a networked computer system.

Gesamte Bond-Datenbank

Los-Nr	Bond-ID	Modul	Chip	Draht	Datum	Uhrzeit	US-Leistg	t20	t50	t80
4711-A	1234560	4	2	1	11.11.95	######	89	18	28	39
4711-A	1234561	4	2	2	11.11.95	######	95	20	30	41
4711-A	1234562	4	2	3	11.11.95	######	90	17	26	37
4711-A	1234563	4	2	4	11.11.95	######	92	20	30	41
4711-A	1234564	4	2	5	11.11.95	######	98	22	33	44
4711-A	1234565	4	2	6	11.11.95	######	89	19	29	40
4711-A	1234566	4	2	7	11.11.95	######	94	17	26	37
4711-A	1234567	4	2	8	11.11.95	######	95	21	32	43
4711-A	1234568	4	2	9	11.11.95	######	89	22	32	43
4711-A	1234569	4	2	10	11.11.95	######	93	15	19	24
4711-A	1234570	4	2	11	11.11.95	######	93	18	27	38
4711-A	1234571	4	2	12	11.11.95	######	95	19	28	39
4711-A	1234572	4	2	13	11.11.95	######	92	20	31	42
4711-A	1234573	4	2	14	11.11.95	######	92	17	26	37
4711-A	1234574	4	3	1	11.11.95	######	90	18	27	38
4711-A	1234575	4	3	2	11.11.95	######	91	28	44	71
4711-A	1234576	4	3	3	11.11.95	######	97	18	27	38
4711-A	1234577	4	3	4	11.11.95	######	91	22	33	44
4711-A	1234578	4	3	5	11.11.95	######	97	19	29	40
4711-A	1234579	4	3	6	11.11.95	######	92	22	33	44
4711-A	1234580	4	3	7	11.11.95	######	97	19	28	39
4711-A	1234581	4	3	8	11.11.95	######	90	22	33	44
4711-A	1234582	5	2	1	11.11.95	######	99	22	33	44
4711-A	1234583	5	2	2	11.11.95	######	96	21	31	42
4711-A	1234584	5	2	3	11.11.95	######	90	20	30	41
4711-A	1234585	5	2	4	11.11.95	######	95	20	30	41
4711-A	1234586	5	2	5	11.11.95	######	98	21	32	43
4711-A	1234587	5	2	6	12.11.95	######	95	19	28	39
4711-A	1234588	5	2	7	13.11.95	######	96	21	32	43
4711-A	1234589	5	2	8	14.11.95	######	98	19	28	39
4711-A	1234590	5	2	9	15.11.95	######	97	18	27	38
4711-A	1234591	5	2	10	16.11.95	######	90	12	16	18
4711-A	1234592	5	2	11	17.11.95	######	97	18	26	37
			Auszug der Problembonds							
4711-A	1234569	4	2	10	35014	0,5455	95,7	15	19	24
4711-A	1234575	4	3	2	35014	0,5456	95	28	44	71
4711-A	1234591	5	2	10	35019	0,5457	94,3	12	16	18

figure 5:
suspect bonds are highligted in the bond data bank

Among the many advantages this brings the user is interested primarily in identifying potentially troublesome bonds, of which two types occur particularly frequently:

- **Imaginary or air touchdown:** In this case a touchdown signal is sent to the bonder although the wire is not actually in contact with the bond pad on the substrate. This happens when foreign material such as a dust particle is caught under the wire. The subsequent pulse of ultrasonic power blasts away the dust speck but the wedge cannot move down enough to make proper contact and consequently only small deformation of the wire occurs. The resulting bond is inadequate but the bonder registers a high deformation because of the large Z movement of the wedge after the initial touchdown on the dust particle. These imaginary deformations are identifiable because they occur right at the start of a bond sequence and are characterised by a rapid increase in deformation - see curve 2 in *figure 6.*

- **Creeping Deformation:** In this case the bond surfaces are contaminated, usually organic contamination and bond formation can only begin after an abnormally long cleaning phase. Cleaning is accomplished by rubbing the wire on the bond pad for an extended period of time, with the result that deformation starts much later than usual and often only a slow rate of deformation is attained - see curve 3 in *figure 6*.

These typical problem bonds are identifiable by the BPC either because the bond

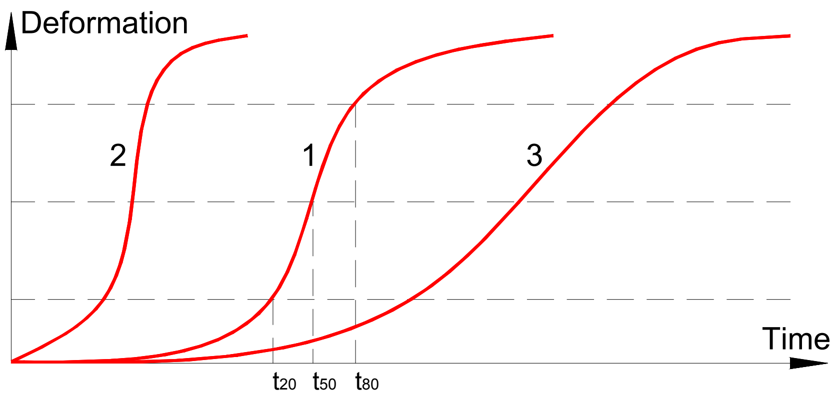

figure 6:
A normal bond and two problem bonds

curves happen very quickly and are seen the left of the monitor display and/or have a very steep slope, or are moved well to the right and have a very gradual slope. The user can select these bonds from the database, for example, by filtering all bonds based on their typical deformation value. With a single SQL command the average t_{50} can be determined and a list displayed of those bonds that exceed or fall short of the average by a factor of three. In the same way, the 15 bonds with the shortest or longest t_{50} values can be displayed or the standard deviation of all t_{50} can be determined then all the bonds with more than three times the standard deviation can be listed. Alternatively the bonds which form very quickly or slowly can be selected, i.e. where the difference between t_{20} and t_{80} is very small or very high. An important strength of the data base organisation is that F&K Delvotec does not prescribe and limit the method of data processing but allows the user to determine what is to be analysed and in which way. Thus the user can make simple, quick screenings just as well as complicated trend plots from millions of bonds over an extended time period.

It is proving to be particularly efficient for the user to save the bond data together with the magazine number whenever a production lot is finished or when a magazine is reloaded on the bonder and then to process the data immediately. The operator is presented with a short list of those bonds selected by the pre-defined criteria as described above. The list is attached to the magazine which is taken to a visual inspection station where the questionable bonds, which are identified by the print out of the module number, chip number and wire number, are inspected very carefully and may be subjected to a pull test. Recording the pull test values at the same time allows a correlation between the actual pull test values and the non-destructive indication of potential problem areas from the BPC monitoring to be established. Subsequently wires removed during pull test can be rebonded using semi-automatic programmable bonders making the complete repair sequence extremely efficient and reliable - see *figure 7*.

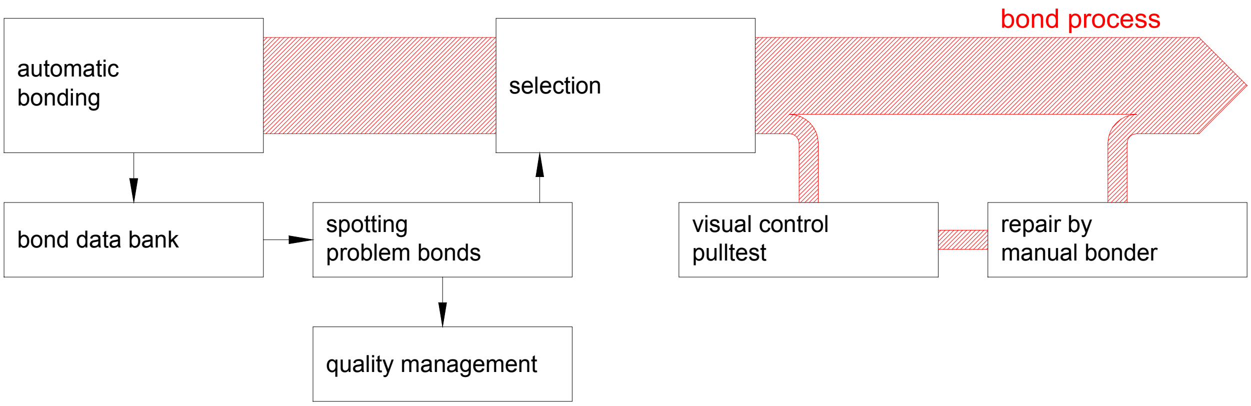

figure 7: BPC schematic

Additional benefits

As the data base with the uniquely identified bonds is not saved on the individual bonder but is stored off-line via a network, it can be evaluated from any workstation. A head of department can check the data for every individual bond from his desk and can also evaluate groups of bonds from larger combinations such as different lots of substrates or bonding wire or different types of circuit. Usually the more constant the material used the more homogenous the bond curves. For example the standard deviation of t_{50} can be taken as a measure of the consistency of the bonds and used to compare different machines and materials; or it can be defined as a standard and used for incoming inspection testing. F&K Delvotec`s smallest wire bonder, the model 5430, also has BPC capability and can be used for a very telling incoming inspection of substrates and chips.

Bond monitoring even brings benefits in the legal domain because data for every single bond is registered and saved. Manufacturers are liable for damages caused by the failure of their manufactured products. The BPC data can show years afterwards whether or not the process was within the prescribed limits when the questionable bonds were made, what deviations were current, whether or not the bonder ran continuously or was out of service shortly before or after the event because the real time when a bond is made is recorded; in other words, if the manufacturing process was under control at the time or not. Today, in the age of zero defect manufacturing, where the highest possible traceability for each component is demanded, this constitutes a major contribution to quality assurance.

Author

Dr. Farhad Farassat is majority owner and president of F&K Delvotec GmbH and holder of numerous European and international patents in the bonding field.